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Phased High-Power Laser Transmisssion Through Optical Fiber Cables

Gerald T. Moore

University of New Mexico
Center of Advanced Studies
Department of Physics
800 Yale Blvd. NE
Albuquerque, NM 87131

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This report has been approved for publication.

A. Gavrielides

ATHANASIOS GAVRIELIDES
Senior Physicist

FOR THE COMMANDER

Roberta M. Ewart

ROBERTA M. EWART, Major, USAF
Chief, Solid-State Lasers & Nonlinear Optics Branch

R. Earl Good

R. EARL GOOD, SES
Director, Directed Energy

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The University of New Mexico
Dept. of Physics and Astronomy
800 Yale Blvd. NE
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13. ABSTRACT *(Maximum 200 words)*
The research carried out under this contract included the development and modeling of solid-state optical sources, including devices based on optical parametric oscillation, Raman oscillation, and harmonic generation. Devices pumped by solid-state lasers and using multiple stages of nonlinear frequency conversion were studied. Regimes of operation offering extended tuning ranges, multiple wavelength generation, high efficiency, or low threshold were identified. This research also included modeling of solid-state lasers, such as Tm:YAG, Yb:YAG, and upconversion fiber lasers, as well as studies of dynamical instabilities in semiconductor lasers.

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1. Phased High-Power Laser Transmission through Optical Fiber Cables

1.1. Statement of the Problem

In response to changes in Air Force research priorities at the Phillips Laboratory and its successor, the Air Force Research Laboratory (AFRL), the research tasks being carried out by University of New Mexico (UNM) personnel under this contract differed from the tasks described in the original statement of work. One area of research investigated was the development and modeling of tunable solid-state optical sources. This included modeling of both cw and synchronously pumped mid-infrared optical parametric oscillators (OPOs) based on periodically poled lithium niobate (PPLN) and pumped at 1.064μm. These devices have been operated at AFRL/DELO. We performed theoretical analysis and numerical modeling on a number of novel devices for optical frequency conversion based on optical parametric oscillation, Raman oscillation, and/or harmonic generation. The objectives of frequency conversion include tunability, high efficiency, low threshold, and good beam quality. A number of proposed devices which promise to fulfill some or all of these objectives are described below and in our published papers. Our three-dimensional modeling made use of a code developed previously by G. T. Moore and extended during this contract. A new numerical code was also developed for faster numerical modeling of OPO devices with cylindrical symmetry, using the fast Hankel transform.

A second area of research investigated was the modeling of solid-state lasers. This work included modeling of Yb:YAG lasers, Tm:YAG lasers, and Pr^{3+} ZBLAN up-conversion fiber lasers.

A third area of research consisted of an experimental investigation of dynamical instabilities associated with optically injected semiconductor lasers. This work included studies of frequency entrainment, periodic attractors, suppressed-carrier modulation, and other dynamical effects.

1.2. Summary of Important Results

1.2.1. Frequency Conversion Based on Optical Parametric Oscillation

Design studies were made for cw PPLN OPOs needed at AFRL for mid-IR generation. These devices were constructed by AFRL scientists and produced multi-Watt levels of mid-IR radiation.

Optical parametric oscillation can be combined with intracavity sum-frequency generation (SFG) of pump and signal, intracavity second-harmonic generation (SHG) of the signal, or intracavity difference-frequency mixing (DFM) of the signal and idler. Devices which use multi-stage intracavity frequency conversion can extend the OPO tuning range or increase the efficiency. For example, the OPO-DFM device can in principle double the efficiency with which the idler frequency is generated. In some cases both internal and external DFM processes can be used to generate up to three idler photons per pump photon [20]. Testing the OPO-DFM concept experimentally was the subject of UNM graduate student M. E. Dearborn's doctoral dissertation research [10], [11], [21], [24] carried out at AFRL/DELO during the period of this contract. Our analysis in support of the OPO-DFM experiments being performed by M. Dearborn included calculations of efficiency, competing nonlinear processes in the DFM crystal, and sensitivity to noncollinearity.

We also did three-dimensional modeling of a Q-switched OPO based on PPLN, incorporating both internal and external stages of difference-frequency mixing [20]. This device was calculated to produce idler radiation at 3.9μm with 237% quantum efficiency in a near diffraction-limited beam.

We studied the plane-wave dynamics for OPO-SFG and OPO-DFM where the two processes are simultaneously phase-matched in the same crystal. OPO-SFG appears less interesting, since complete pump depletion only occurs in the limit of zero gain. Simultaneous OPO-DFM can be efficient over a large dynamic range, and should be realizable in PPLN using a 1.064μm pump. The plane-wave equations for simultaneous OPO-DFM were solved in terms of Jacobi elliptic functions. A preliminary report of this analysis has been written. Three-dimensional simulations have also been carried out. While possibilities exist for such simultaneous phase-matching in a single grating in PPLN, the lack of tunability may make this process of limited practical interest. Nevertheless, this process could be observed at AFRL/DELO by temperature tuning a currently operating cw PPLN OPO. Enhancement of idler generation is expected.

Modeling of a synchronously pumped OPO based on PPLN currently operating at AFRL showed that the cavity-length tuning of OPO efficiency can be well accounted for by a plane-wave model with five

adjustable parameters. Experimental efforts are currently underway at AFRL aimed at obtaining additional data on the synchronously pumped PPLN OPO to compare with this theoretical model.

We studied ways of tuning the currently operating synchronously pumped PPLN OPO by means of noncollinear phase matching. Appreciable tuning should be possible in an arrangement where the pump and nonlinear grating wave vectors are collinear, but the signal and idler have equal but opposite transverse wave vectors.

Our studies of multi-stage intracavity frequency conversion have emphasized the importance of states of complete pump depletion (CPD) to efficient operation. We explored the possibilities which arise by inserting an additional high-gain OPO crystal in these devices, in addition to the OPO crystal where conversion takes place at saturation [5]. The CPD states are unaffected by this gain crystal, but the high small-signal gain can promote rapid saturation (and thus higher efficiency) in repetitively Q-switched devices. The idler is outcoupled both before and after this gain crystal. The gain crystal is dormant after saturation. Both plane-wave modeling and modeling in three spatial dimensions were used to study intracavity SFG of the pump and signal, SHG of the signal, and DFM of the signal and idler. Applications were studied for ultraviolet and infrared generation, using ring resonators with three flat mirrors with injection seeding at the signal frequency. Excellent conversion efficiency and beam quality were obtained after saturation in some three-dimensional simulations, although there was a spike in the beam-quality parameter M^2 as saturation occurred. However, in other simulations the beam quality continued to deteriorate and effects of FFT aliasing became evident. It is not yet clear whether this deterioration is a physical effect or a numerical artifact.

The problem of poor beam quality in Q-switched OPOs can be alleviated by injection seeding at the signal or idler wavelength. We evaluated an alternative to injection seeding of critically phase-matched OPOs based on use of a non-planar resonator which effectively makes both transverse dimensions critical. We made three-dimensional simulations of OPOs in which non-planar resonators are used to transpose or rotate (by 90°) the signal field after each round trip. We hoped that such resonators would give improved beam quality. However, the numerical simulations indicate that such resonators are not helpful.

We did three-dimensional modeling of a synchronously pumped SFG-OPO device for converting 1.03μm Yb:YAG radiation to 0.589μm sodium resonance radiation, using LBO for the SFG crystal and PPLN for the OPO crystal. Up to 76 % power conversion was obtained in a nearly diffraction-limited beam. We think such conversion should be possible even with average powers of hundreds of watts, if the resonance radiation is outcoupled before the PPLN crystal.

We also did three-dimensional modeling of a cw PPLN OPO for converting a 1 W diode laser at $\lambda_p = 0.98\mu$m to idler radiation at 2.9μm. We found that double passing the pump and idler through the 5 cm interaction length increased the small-signal gain from 2.1 % to 7.8 %. About 34 % power conversion to the idler wavelength is predicted. A near optimal phase relation for the fields on the return trip can be obtained by using a PPLN wafer with a slight wedge between the grating planes and the end of the wafer and translating the wafer transversely. This concept was extended to describe a periodic optical parametric oscillator (POPO) [13], [23]. The POPO uses N_c 5-cm PPLN crystals in a fan-fold configuration with focusing after each interaction and retroreflection to achieve an effective $10N_c$ cm interaction length for singly resonant oscillation. Using $N_c = 2$, thresholds as low as 100 mW for down-conversion of 0.8μ radiation were calculated. Pumping with a diode laser should be possible. High-efficiency conversion to the nonresonant generated field is found. Resonating the idler should minimize thermal and photorefractive effects, which suggests that room-temperature operation may be possible. The device shows remarkably good agreement between the results of plane-wave and three-dimensional calculations, when these calculations are related using an overlap integral similar to that of Boyd and Kleinman. Reference [13] analyzes both the periodic optical parametric oscillator (POPO) and periodic second-harmonic generation (PSHG).

A tandem OPO (TOPO) uses the signal of a primary OPO to pump a secondary OPO contained in the same cavity. We studied such a device to efficiently generate three wavelengths simultaneously in different high-transmission infrared bands of atmospheric water vapor, using a monolithic PPLN TOPO.

PPLN becomes absorbing for wavelengths longer than 4μm. For generation of longer wavelengths, using a 1.064μm Nd:YAG pump laser producing long Q-switched pulses, the TOPO concept still appears promising, but another type of crystal is needed for the secondary OPO. We have designed a compact TOPO using PPLN for the primary OPO and zinc germanium phosphide (ZGP) for the secondary OPO. Phase matching in both crystals is noncritical. The device is tunable; typical output wavelengths are 1.8561μm, 4.5249μm,

and $5.5527\mu m$. A resonant $2.4932\mu m$ field pumps the secondary OPO, but is not out-coupled. Curving the end faces of the ZGP provides a stable cavity for both OPOs. The secondary cavity is monolithic standing-wave. The primary cavity is a ring. A TOPO design for cw operation is also being studied. Losses at the $2.4932\mu m$ wavelength appear to be a serious drawback in the cw device.

We have generalized our previous studies of the plane-wave dynamics of the TOPO to cases where the primary and secondary OPOs have different cavity lengths. This would be the case, for example, for the PPLN–ZGP TOPO described above. While the steady-state behavior is independent of the ratio of cavity lengths, the transient behavior and dynamical instabilities do depend on this ratio. Unless one cavity length is a multiple of the other, interpolation is needed to calculate the transient behavior.

In Ref. [8] we analysed a ring OPO in which the the resonant signal pumps a secondary OPO simultaneously phase-matched in the same material. This type of secondary OPO oscillation has been observed experimentally at the Air Force Wright Laboratory using PPLN. The output of the STOPO consists of the primary idler, the secondary signal, and the secondary idler, whose frequencies sum to the pump frequency. Thus, the STOPO serves the same function as the TOPO, except that the TOPO requires two nonlinear elements. Our analysis of the PPLN STOPO indicates that oscillation of the secondary OPO effectively prevents back-conversion of the pump, yielding excellent efficiencies and beam qualities over a large range of pump intensity. Three-dimensional simulations indicate that the optimal cavity reflectivity at the secondary-signal frequency is larger than indicated by plane-wave theory for both the TOPO and the STOPO. We also analyzed a variant of the STOPO where the nonresonant primary field pumps the secondary OPO. This variant is of less practical interest because of its higher threshold for the secondary OPO.

Reference [9] discusses the use of grating-period contours for analyzing quasi-phase-matched devices. We have found this method very useful, especially for devices involving multiple interactions. It also provides a visual way of identifying unwanted interactions which are accidentally phase matched.

1.2.2. Frequency Conversion Based on Raman Oscillation

In Ref. [6] we use both plane-wave analysis and three-dimensional modeling to describe a Raman oscillator containing an intracavity second-harmonic interaction that frequency doubles the circulating first-order Stokes radiation.

In Ref. [15] we use both plane-wave analysis and three-dimensional modeling to analyze a Raman oscillator with intracavity sum-frequency generation of the pump and the circulating first-order Stokes radiation. We find that this device performs well, but only if the SFG crystal precedes the Raman material in the cavity.

1.2.3. Frequency Conversion Based on Harmonic Generation

The plane-wave dynamics of simultaneous second- and third-harmonic generation were studied. Asymptotically complete conversion to the third harmonic was found for a particular ratio of coupling strengths.

We analyzed resonant doubling and tripling of a laser beam in an external cavity which resonates only the first harmonic. A plane-wave analysis using the solutions for two- and three-wave mixing in terms of Jacobi elliptic functions was used. Linear and nonlinear phase shifts of the first harmonic due to cavity detuning and imperfect phase matching in the nonlinear crystals were considered in the analysis and appear to lead to interesting switching behavior. Sideband generation caused by down-conversion of the second harmonic in the resonant doubler was also investigated. Future experiments are possible using a resonant doubler built by C. Denman at AFRL.

In Ref. [14] we investigated the resonant tripler as a promising method for efficient frequency tripling of low-power cw or cw mode-locked laser sources. Both plane-wave analysis and three-dimensional numerical modeling were used to optimize the design parameters. Tripling of 350 mW cw $1.319\mu m$ radiation in PPLN and tripling of 2.6 kW peak-power mode-locked $1.064\mu m$ radiation in lithium triborate were modeled. High conversion efficiencies to the third harmonic are predicted.

Our success in obtaining excellent agreement between plane-wave and three-dimensional modeling of the POPO and PSHG devices led us to try the same approach with the resonant tripler. This approach, which involves using an overlap integral of the Boyd-Kleinman type to apply plane-wave solutions to tightly focused Gaussian beams, proved successful in describing almost all aspects of a resonant tripler based on PPLN, except for the effects of phase mismatch in the sum-frequency crystal. However, even these effects could be accounted for by a modified plane-wave (MPW) approach based on coupled-wave theory. Although

the MPW equations must be solved numerically, this is much simpler than solving the three-dimensional equations. Both the plane-wave and MPW approaches work well only if the nonlinear drive is weak. However, the extension of the MPW approach to include higher-order modes appears to merit further study.

An idea we developed which seems worth exploring experimentally is to try quasi-phase matching CLBO by means of surface etching. The maximum nonlinear coefficient for three e-waves occurs at $\phi = 45°$ and $\theta = 35.3°$. CLBO has a low refractive index, so that light can be propagated along the etched surface without significant reflections by using a suitable index-matching fluid. The etched grating needed for doubling $1.064\mu m$ radiation has a $44\mu m$ period. The nonlinear interaction is nearly noncritical, and long crystal lengths are available.

During the final weeks of technical effort on this contract we began theoretical work on novel methods for frequency doubling or tripling which are nonresonant and are not sensitive to the relative phases of the fields incident on the crystals, but which require recirculation of the fields. We have compared the dynamics of these devices with the usual single-pass interactions and find that the new devices can perform more efficiently in many circumstances. For example, doubling using type-II phase matching is usually accomplished by injecting equal amounts of each polarization at the fundamental frequency. Our recirculating doubler injects only one polarization, but the emerging first harmonic has its polarization rotated by 90° (for example by a half-wave plate) and is reinjected for a second pass through the crystal. The efficiency of the recirculating doubler rises faster with pump intensity than the traditional doubler (it is four times as efficient at low intensity) and at high intensity the instantaneous power generated at the second harmonic can exceed the fundamental power. In some circumstances a period-two limit cycle can occur, and power-conversion efficiencies approaching 200% are obtained on every other pass, with little second harmonic generated on the alternate passes. A recirculating tripler can be constructed by inserting a crystal for sum-frequency generation (SFG) of the first and second harmonics into the recirculating doubler. The most interesting configuration is where the incident first harmonic first interacts in the SFG crystal. Second harmonic generated in the SHG crystal is recirculated to the SFG crystal and coupled out, along with the third harmonic, after this crystal. Another scheme, which could be used with either a type-I or type-II SHG interaction, simply couples out the higher harmonics after the SFG crystal and the first harmonic after the SHG crystal. Both these schemes give efficient third-harmonic generation with shorter SFG crystals than single-pass tripling, since the full pump power is incident on the SFG crystal. This is important, since walk-off in the SFG crystal is often a limiting factor. An Invention Disclosure describing these devices in detail is being submitted to UNM.

1.2.4. Modeling of Solid-State Lasers

Thermal loading is a major problem in high-power solid-state lasers. We studied the extraction efficiency and thermal lensing effects in Tm:YAG lasers. We also studied the effects of excited-state absorption and upconversion on the performance of erbium germanosilicate cw lasers.

The Yb:YAG laser was modeled [7] as a two-manifold system and, by applying our previously developed theory, the unusually wide tuning curve of this solid-state laser was explained. Work aimed at optimizing the pulse energy output of end-pumped Q-switched lasers by varying the parameters under experimental control was also carried out. The relevant equations were derived, and computational modeling was carried out.

In Ref. [12] we modeled the steady-state threshold and extracted power of a two-photon incoherently pumped upconversion fiber laser.

1.2.5. Nonlinear Dynamics of Semiconductor Lasers

An experimental investigation was made of the nonlinear resonances exhibited by an optically injected semiconductor laser as a function of the frequency detuning of the laser from the externally injected signal and for weak injection strength. In the asymptotic limit, for certain laser parameter values, these phenomena were investigated analytically, as well, in order to determine the origin of these instabilities. Details of much of this work are available in published papers [16]–[19] and have also been presented in invited and contributed talks at conferences [25]–[27].

2. List of Publications and Technical Reports

Note: Items 1–4 were published or awarded during this contract, but are based on work completed prior to this contract.

1. G. T. Moore and K. Koch, "Phasing of tandem crystals for nonlinear optical frequency conversion," Opt. Commun. **124**, 292–294 (1996).
2. G. T. Moore and K. Koch, "The tandem optical parametric oscillator," IEEE J. Quantum Electron. **32**, 2085–2094 (1996).
3. S. H. Chakmakjian, M. Gruneisen, K. Koch, and G. T. Moore, "Phased cascading of multiple nonlinear optical elements for frequency conversion," Patent No. 5500865, awarded Mar. 19, 1996.
4. G. T. Moore, K. Koch, and E. C. Cheung, "Optical beam scanner with rotating transmissive optics," Patent No. 5646764, awarded July 8, 1997.
5. G. T. Moore, K. Koch, and M. E. Dearborn, "Gain enhancement of multi-stage parametric intracavity frequency conversion," IEEE J. Quantum Electron. **33**, 1734–1742 (1997).
6. K. Koch, G. T. Moore, and M. E. Dearborn, "Raman oscillation with intracavity second-harmonic generation," IEEE J. Quantum Electron. **33**, 1743–1748 (1997).
7. P. Peterson, M. P. Sharma, and A. Gavrielides, "Modeling of Yb:YAG tuning curves," Opt. Commun. **134**, 155–160 (1997).
8. G. T. Moore, K. Koch, M. E. Dearborn, and M. Vaidyanation, "The simultaneously phase-matched tandem optical parametric oscillator," IEEE J. Quantum Electron. **34**, 803–810 (1998).
9. K. Koch and G. T. Moore, "A tool for analyzing quasi-phase-matched devices," Opt. Commun., submitted for publication.
10. M. E. Dearborn, K. Koch, G. T. Moore, and J. C. Diels, "Greater than 100% photon-conversion efficiency from an optical parametric oscillator with intracavity difference-frequency mixing," Opt. Lett. **23**, 759–761 (1998).
11. M. E. Dearborn, "Synchronously pumped optical parametric oscillator with intracavity difference frequency mixing," Optical Sciences Ph. D. dissertation, University of New Mexico (1998).
12. P. Peterson and M. P. Sharma, "Modeling of threshold and extraction efficiency in Pr^{3+} ZBLAN upconversion fiber lasers using 2-photon pumping," Opt. and Quantum Electron. **30**, 161–173 (1998).
13. G. T. Moore and K. Koch, "Efficient frequency conversion at low power using periodic refocusing," J. Opt. Soc. Am. B, submitted for publication.
14. K. Koch and G. T. Moore, "Singly resonant cavity-enhanced frequency tripling," J. Opt. Soc. Am. B, submitted for publication.
15. K. Koch, G. T. Moore, and M. E. Dearborn, "Raman oscillation with intracavity sum-frequency generation," IEEE J. Quantum Electron., submitted for publication.
16. P. M. Varangis, A. Gavrielides, T. Erneux, V. Kovanis, and L. F. Lester, "Frequency entrainment in optically injected semiconductor lasers," Phys. Rev. Lett. bf 78 2353–2356 (1997).
17. A. Gavrielides, V. Kovanis, P. M. Varangis, T. Erneux, and G. Lythe, "Coexisting periodic attractors in injection locked diode lasers," Quantum and Semiclassical Opt. **9**, 785–796 (1997).
18. P. M. Varangis, A. Gavrielides, V. Kovanis, T. Erneux, and L. F. Lester, "All-optical double-sideband suppressed-carrier modulation of semiconductor lasers," J. Appl. Phys. **84**, 8071–8073 (1998).
19. P. M. Varangis, A. Gavrielides, V. Kovanis, and L. F. Lester, "Linewidth broadening across a dynamical instability," Phys. Lett. A, submitted for publication.

3. List of Technical Presentations

NOTE: Some references are to published abstracts of technical presentations.

20. K. Koch and G. T. Moore, "Optical parametric device for efficient generation of radiation in the 3.9 micrometer range," in *Nonlinear Optics: Materials, Fundamentals, and Applications*, Vol. 11, 1996 OSA Technical Digest Series (Optical Society of America, Washington DC, 1996), pp. 90–91.
21. M. E. Dearborn, K. Koch, G. T. Moore, and J. C. Diels, "Greater than 100% photon-conversion efficiency from an optical parametric oscillator with intracavity difference-frequency mixing," OSA Trends in Optics and Photonics Vol. 19, Advanced Solid State Lasers, W. R. Bosenberg and M. M. Fejer, eds. (Optical Society of America, Washington, DC 1998), pp. 240–244.
22. K. Koch, G. T. Moore, and N. A. Brilliant, "Singly resonant cavity-enhanced frequency tripling," in *Nonlinear Optics '98: Materials, Fundamentals, and Applications Topical Meeting* IEEE Catalog #:98CH36244 (IEEE, Piscataway, NJ, 1998), pp. 48–50.

23. G. T. Moore and K. Koch, "Low-threshold periodic optical parametric oscillator," in *Nonlinear Optics '98: Materials, Fundamentals, and Applications Topical Meeting* IEEE Catalog #:98CH36244 (IEEE, Piscataway, NJ, 1998), pp. 45–47.
24. M. E. Dearborn, K. Koch, G. T. Moore, and J. C. Diels, "Tunable parametric downconverter with photon-conversion efficiencies greater than 100%," in *Nonlinear Optics '98: Materials, Fundamentals, and Applications Topical Meeting* IEEE Catalog #:98CH36244 (IEEE, Piscataway, NJ, 1998), pp. 276–278.
25. P. M. Varangis, A. Gavrielides, V. Kovanis, T. Erneux, and L. F. Lester, "Nonlinear resonances in optically injected semiconductor lasers," European Quant. Electron. Conference (EQEC), Hamburg, Germany (1996). Paper QThC2.
26. P. M. Varangis, A. Gavrielides, V. Kovanis, and T. Erneux, "Observing dynamic isolas in an optically injected semiconductor laser," QELS 1996, Anaheim, CA, June, 1996.
27. A. Gavrielides, V. Kovanis, P. M. Varangis, T. Erneux, and T. B. Simpson, "Subharmonic resonances in an optically injected semiconductor laser," (invited paper) SPIE Proc. **2693** 654, San Jose, CA (1996), (W. W. Chow and M. Osinski, Eds.).

4. List of Participating Personnel

All personnel financially supported by this contract are or were affiliated with the Department of Physics and Astronomy of the University of New Mexico. The work was performed at AFRL/DELO and its predecessor organizations in the Phillips Laboratory. The Principal Investigator, Dr. Gerald T. Moore, worked full-time on this project during the entire time of the technical effort. Dr. Mohinder P. Sharma worked full-time on this project during the first year of the technical effort. UNM graduate student Petros Verangis was partially supported by and trained in areas pertinent to this contract. Although not financially supported by this contract, UNM graduate student and Air Force Captain Michael E. Dearborn carried out his dissertation research for the Ph. D. degree in Optical Sciences while working at AFRL/DELO under the guidance of Karl Koch of AFRL/DELO and Dr. Moore. This degree was awarded to him by UNM in 1998.

5. Inventions

An Invention Disclosure entitled "Nonresonant Recirculation Configurations for Optical Frequency Doubling and Tripling" is being filed with the University of New Mexico. The invention described therein was conceived during work on this contract. The inventors are Gerald T. Moore and Karl Koch.

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